NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

NASA SP-8001

BUFFETING DURING ATMOSPHERIC ASCENT

MAY 1964
Revised
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all previously issued monographs in this series can be found at the end of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniform design requirements for NASA space vehicles.

This monograph is a revision of a monograph issued in May 1964. The original and revisions were prepared by H. A. Cole, Jr., and A. L. Erickson of Ames Research Center, and by A. G. Rainey of Langley Research Center. The monograph was revised under the cognizance of Langley Research Center as the lead center for structures criteria. The revisions consist primarily in the addition of more recent references which indicate that the buffeting-category boundaries presented are still valid, although less conservative than originally anticipated.

November 1970

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BUFFETING DURING ATMOSPHERIC ASCENT

1. INTRODUCTION

Buffeting is a repeated loading of a structure by an unsteady aerodynamic flow. The occurrence of buffeting during atmospheric ascent depends primarily on the shape of the vehicle; its severity depends on dynamic pressure, Mach number, and angle of attack, as well as shape. Unfavorable shape factors include protuberances, swellings, and abrupt changes in vehicle profile, especially at or near the forward end of the vehicle.

Buffeting may cause overall vehicle-bending oscillations, shell-breathing oscillations, and vibration of structural panels. Equipment and sensors located near structural panels subjected to buffeting may fail or be otherwise adversely affected by the associated vibration.

When possible, the vehicle should be designed to minimize buffeting through the use of favorable configurations. If this is not possible, the undesirable effects (i.e., oscillating pressures, aeroelastic responses, and possible impairment or degradation of human functions and equipment operation) must be determined and provided for in the structural design.

Related problems, such as vibration, acoustics, and flutter, will be considered in detail in other monographs.

2. STATE OF THE ART

Buffeting is a problem that has plagued aircraft designers as far back as 1930 and, hence, has been investigated extensively. A review of buffeting work on aircraft is given in reference 1. Generally, buffeting is associated with separation of the boundary layer and transition to turbulent flow. Considerable progress has been made in recent years to advance boundary-layer and turbulent-flow theory, and an excellent review is given by von Karman in his 1959 Guggenheim Memorial Lecture (ref. 2). However, a satisfactory solution of the buffeting phenomenon by analytical means has not been found and, at present, experimental results must be used for prediction of buffeting loads.

Early work on turbulent flow by Taylor, von Karman, and Dryden was developed along the lines of statistical analysis; a review of this work is given in reference 3. Particular application of statistical concepts to the buffeting problem is introduced by Liepmann in reference 4, in which he considers parallel research from communications engineering by Rice (ref. 5) and Wiener (refs. 6 and 7). Further applications of statistical analysis are contained in references 8 to 10. These methods imply that the structural system is a linear system and that the input force is a sample function of an ergodic random process. Generally, the problem can be separated into two parts: (1) a definition of the input forces as a stochastic process and (2) a definition of the system frequency response. When these quantities are defined, the output quantities can be obtained in statistical terms.

Wind-tunnel measurements of buffeting-input forces are reported for a wide range of space-vehicle nose shapes in references 11 to 18; the buffeting forces reported in reference 11 were applied in the calculation of buffeting loads on the Atlas-Able V given in reference 19. Another example is contained in reference 15 for the Mercury-Atlas vehicle. Several assumptions were made in these analyses which indicate a lack of information in the present state of the art. For example, it was necessary to assume that all the buffeting pressures acted together because spatial correlation of pressures was not well known. In addition, scaling of the spectra was assumed to be in accordance with reduced frequency. Although there is some doubt regarding the scaling laws because separation effects can vary greatly, depending on the condition of the boundary layer (ref. 20), there is some evidence (refs. 16 and 21) that the assumed scaling relationships are valid.

The already complex problem of buffeting was further complicated by the discovery of unstable aerodynamic effects of "hammerhead" noses (ref. 22). These results indicated that buffeting response could be greatly amplified by destabilizing aerodynamic forces, and buffeting analyses should therefore include aerodynamic, as well as structural, damping. Further information on aerodynamic damping is given in references 23 to 26. The unstable damping of hammerhead launch vehicles has also raised the question of the stability of blunt-nose flared vehicles which are similar to the entry-body configurations found to be unstable in references 27 and 28. Analysis of aerodynamic damping for this type of vehicle is given in references 29 to 31. In this method, induced loads caused by separated flow are determined from static aerodynamic data, and the distance from the separation point to the induced loading is used as the characteristic length in a quasi-steady-state analysis. This method shows promise for cases where the characteristic length is clearly defined.

One of the major problems that arise in the prediction of buffeting is the large number of geometric configurations that are possible with various sizes of payloads and rocket stages. Because of this, buffeting data are rarely available for any particular vehicle in the preliminary design stage. To get around this problem, a method has been developed by Albert L. Erickson of the Ames Research Center which correlates buffeting loads with the minimum pressure and adverse pressure gradients calculated from slender-body theory. With this method, any geometric shape can be classified and judged to fall within several categories of buffeting flow that have been determined by previous experiments. The slender-body theory, unfortunately, gives unrealistic pressure gradients for sharp steps, and the gradients have to be modified arbitrarily on the basis of previous experience. Since the theory is used to normalize experiment by theory for the purpose of making relative comparisons between configurations, the same simple theory and calculation procedure should always be used in order to produce consistent and valid comparisons. At present, this method has been used for qualitative studies of a number of configurations with various nose shapes, boattail angles, flare angles, stage lengths, and stage-diameter ratios from which the numbers given in the design criteria have been obtained.

In summary, no general analytical method has been found to solve the buffeting problem. Consequently, prediction of buffeting rests entirely on wind-tunnel information from scale models. The application of these data is somewhat uncertain because scaling effects of boundary-layer and separation phenomena have not been firmly established. In the present state of the art, buffeting loads are predicted by statistical methods, with the assumption that the structure is a constant-coefficient linear oscillator subjected to random forces that are sample functions of an ergodic random process. In reality, buffeting of the space vehicle is a physical system of a time-varying nonlinear oscillator subjected to a statistically nonstationary random input. Solution of this problem is beyond the state of the art and, hence, the design procedures which are outlined in this monograph are intended to be conservative.

3. CRITERIA

3.1 Examination of Space Vehicles

Space vehicles shall be examined for the existence, type, and intensity of buffeting. Criteria are presented according to geometric shape parameters and pressure-distribution parameters of the vehicle.

3.2 Clean Bodies of Revolution

Configurations which can be defined in terms of the pressure and shape parameters specified in Sections 3.2.1, 3.2.2, and 3.2.3 are considered to be free of buffeting which would cause overall vehicle-bending or shell-breathing oscillations. Buffeting may exist in highly localized areas in the region of fluctuating shock waves.

3.2.1 Pressure Parameters

Configurations with nose shapes that have minimum theoretical incompressible-flow static-pressure coefficients and maximum adverse pressure gradients in the following ranges are considered buffet free as defined in the first paragraph of Section 3.2.

$$0 \leqslant \left(\frac{\Delta p}{q}\right)_{min} \leqslant -0.14 \qquad\qquad 0 \leqslant \left(\frac{d\,\frac{\Delta p}{q}}{d\,\frac{x}{D}}\right)_{max} < 0.2$$

(See Sec. 3.2.2, following.)

3.2.2 Theoretical Pressure-Distribution Equation and Parameter Definition

The theoretical pressure-distribution equation to be used is

$$\frac{\Delta p}{q}(x) = \frac{\partial}{\partial x} \int_{Nose}^{Base} \frac{rr'}{\sqrt{(x-\xi)^2 + r^2}}\, d\xi \qquad (1)$$

where

p = static pressure

q = dynamic pressure

x = longitudinal coordinate of point where pressure is to be calculated

ξ = longitudinal coordinate of point on body

r = body radius at ξ

r′ = $dr/d\xi$

Pressure parameters are defined in figure 1, where D is maximum diameter of nose section.

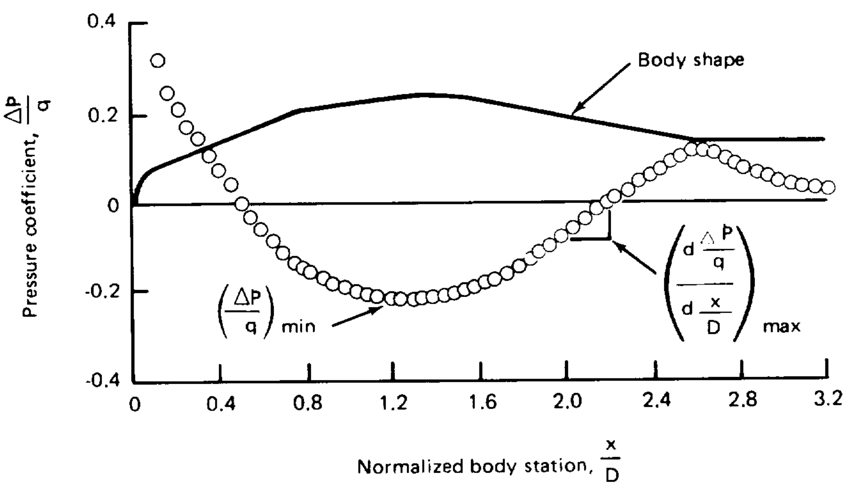
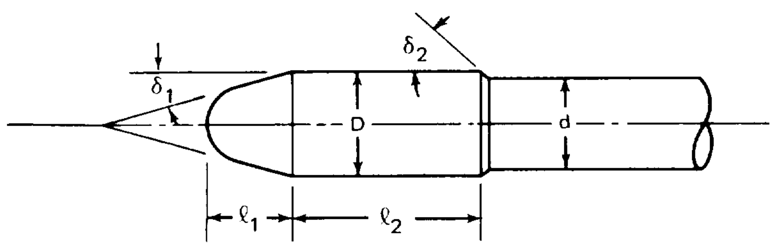


Figure 1.

3.2.3 Shape Parameters

Configurations not conforming to the criteria of Section 3.2.1 because of nose blunting and presence of small steps, but meeting the criteria given in figure 2 are considered buffet free as defined in the first paragraph of Section 3.2.



d = 0.9 D to 1.1 D	
$\ell_1 \geqq 0.80$ D	$\ell_2 > 1.5$ D
$\delta_1 \leqq 15$ deg	δ_2 not critical

Figure 2.

3.3 Buffet-Prone Bodies of Revolution

Configurations that have a separated-wake type of flow or that are liable to destabilizing aerodynamic-damping force require evaluation of buffeting loads and other undesirable buffeting effects. Such configurations are defined in the following paragraphs in terms of pressure and shape parameters.

3.3.1 Separated-Stable Configurations

Separated-stable configurations are defined in terms of pressure and shape parameters as follows (see also Sec. 3.2.2):

$$\left(\frac{d\,\dfrac{\Delta p}{q}}{d\,\dfrac{x}{D}}\right)_{max} \geqq 1.8$$

The above criterion is restricted to configurations having node location, diameter, and length parameters as defined in figure 3, and applies only where a single, straight-line boattail angle is used.

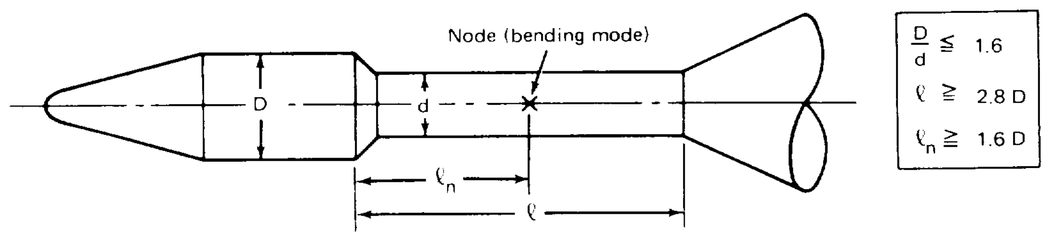


Figure 3.

The restrictions shown in figure 3 are made because of the limited amount of available buffeting data, and are not intended to imply that configurations outside the parameters cannot have separated-stable flow. However, until experimental results are obtained which confirm the pressure gradient criteria outside the limits shown, configurations not conforming to figure 3 shall be treated as possible separated-unstable configurations.

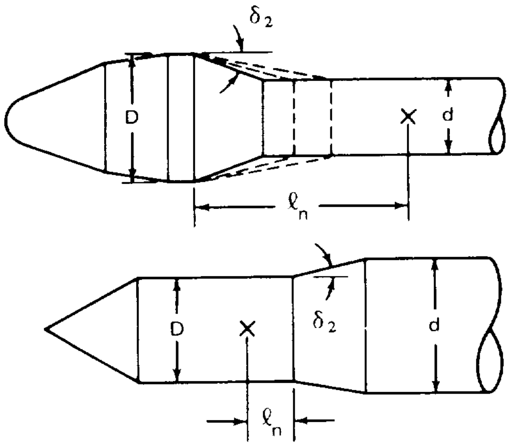
Configurations having cavities (e.g., a compartment with large uncovered blast vents) which might otherwise meet the criteria of Section 3.2.

3.3.2 Separated-Unstable Configurations

Configurations having adverse pressure gradients (see Sec. 3.2.2) in the range below are liable to destabilizing aerodynamic-damping forces.

$$0.2 \leqslant \left(\frac{d\,\dfrac{\Delta p}{q}}{d\,\dfrac{x}{D}}\right)_{max} < 1.8$$

Examples of some undesirable configurations of this class are shown in figure 4.



$\frac{D}{d}$	=	1.6
ℓ_n	=	1.6 D
δ_2	=	10, 15, 20 deg

$\frac{D}{d}$	=	0.75
ℓ_n	=	0.4 D
δ_2	=	13 deg

Figure 4.

3.4 Other Buffet-Prone Bodies

Configurations which are not bodies of revolution, such as winged configurations, may be liable to destabilizing aerodynamic-damping forces, as well as separated flow, and require evaluation of buffeting loads and other undesirable buffeting effects.

4. RECOMMENDED PRACTICES

4.1 Category of Configuration

Practices to be followed in designing space-vehicle systems for buffeting will depend on the category in which the configuration falls, as indicated in Section 3.

4.2 Clean Bodies of Revolution

With well-designed nose shapes, a normal shock will appear with some thickening of the boundary layer downstream, but separated flow will not occur. However, as indicated in references 11 to 13, panels near the shoulders and steps of these shapes will be subjected to a highly localized pressure fluctuation which should be considered in the design of panels and nearby equipment. Data contained in the references cited should permit an adequate determination of the fluctuating pressures, providing these data are used in conjunction with a conservative estimate of the cross-power spectral density of the fluctuating pressure field.

4.3 Buffet-Prone Bodies of Revolution

4.3.1 Separated-Stable Configurations

Separated-stable configurations are subject to buffet pressures of such magnitude and extent that both the local-panel response and the modal response of the vehicle should be considered in the design. For shapes within this category that are similar to the shapes investigated in references 11 to 16, the pressure data available in these references are considered to be adequate for preliminary design. For other configurations which differ significantly from those considered in the references, a wind-tunnel determination of fluctuating pressures on rigid models is recommended. Practices and procedures for these two cases are set forth in the remainder of Section 4.3.1.

Buffet Data Available – A preliminary estimate of the bending moments caused by buffeting can be made by use of appropriate input data from references 11 to 16 in an analysis of the type discussed in references 15 and 19. This type of analysis will generally lead to conservative values of bending loads because of the assumption that all buffet forces act in phase. If the bending moments obtained by this type of analysis do not impose a significant design penalty, it can be considered that the modal-bending aspects of the buffet problem have been satisfied.

If these conservative calculated bending moments are high enough to impose a significant design penalty, a wind-tunnel program is recommended to establish the actual design buffet-bending moments. A satisfactory rigid-model technique using summation of pressure cells is described in reference 22.

For configurations on which the cross-spectral densities of fluctuating pressures are known, a more exact analysis of bending moments can be made (ref. 32) which is not overly conservative. In these cases, further wind-tunnel tests are not necessary and the resulting values of bending moments should be satisfactory for design purposes.

Buffet Data Not Available – For configurations which differ from those for which wind-tunnel data exist, dynamic pressure-cell tests on scale models are recommended. The technology for conducting these tests is well established, as indicated in references 11 to 16. Scaling parameters that should be satisfied are Mach number, Reynolds number, and reduced frequency. The Mach number can be satisfied, but generally the Reynolds number cannot be matched in existing facilities. If the Reynolds number is not high enough to ensure a turbulent boundary layer on the model at the separation point, it is recommended that artificial roughness be used to trip the boundary layer. For a particular vehicle, reduced frequency is satisfied as follows:

$$f_M = f_{FS} \frac{D_{FS}}{D_M} \frac{V_M}{V_{FS}} \tag{2}$$

where

f	=	frequency
D	=	characteristic dimension
V	=	velocity
M	=	model
FS	=	full scale

For example, the model frequency of a 1/6-scale model tested in air which corresponds to a full-scale frequency of 200 Hz is

$$f_M = 200 \times \frac{6}{1} \times \frac{1}{1} = 1200 \text{ Hz}$$

The frequency environment of importance to structural modes and equipment generally does not exceed 2000 Hz on a full-scale vehicle. However, this figure imposes severe frequency requirements on pressure cells for small-scale models, and for this reason the model should be made as large as possible. The actual frequency requirements will depend on evaluation of the possible response of the various structural modes, structural panels, and equipment to buffeting forces.

After the buffet-pressure data have been obtained, the design evaluation should proceed as described earlier in this section for configurations with buffet data available.

4.3.2 Separated-Unstable Configurations

For separated-unstable configurations, a dynamic-model wind-tunnel program is recommended for the determination of aerodynamic aspects of the system stability and the model's bending loads. The preferred dynamic-model techniques are the partial-mode technique described in reference 22 and the complete dynamic-model technique described in references 23, 25, and 33. The partial-mode technique simulates the modal response of the complete space-vehicle system by use of rigid partial models supported on springs in a manner that permits pitching about the nodal points at the correct scaled frequency. The complete dynamic-model technique employs a complete aeroelastically scaled model supported on soft springs in a manner that permits response in the free-free bending modes. Both techniques employ excitation of the model for the determination of aerodynamic damping derivatives. The measured dynamic response of the models is used to predict the full-scale bending moments.

4.4 Other Buffet-Prone Bodies

For other buffet-prone body configurations, a dynamic-model wind-tunnel program as described in Section 4.3.2 is recommended.

4.5 Special Considerations

The flow on some parts of buffet-prone shapes will result in pressure fluctuations that have relatively high energies at high frequencies. These high-intensity pressures can lead to structural fatigue and/or equipment malfunctions. For these conditions, special emphasis should be placed on design features for minimizing structural damage and equipment malfunctions as recommended in reference 34. However, both these problems are considered to be too complex for complete reliance on available analytical procedures; it is therefore recommended that appropriate tests be performed.

For manned vehicles, special emphasis should be placed on design features to avoid those combinations of frequency and acceleration known to have adverse effects on man's health or performance. Human tolerance criteria are reviewed in reference 35, and additional data are given in references 36 and 37.

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